

Molecular Beam Epitaxy for InAs/AlSb High Electron Mobility Transistors

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Problem #1: FET applications require high sheet charge density; Si is predominantly an acceptor in AlSb and GaSb

- Solution: Use chalcogens such as Te as an n-type dopant in AlSb.
 - Memory effects
- Solution: “As soak” technique--expose Al monolayer to beam of As \sim 100 Å above the InAs.
 - Results in $n_s = 1.5\text{-}2.0 \times 10^{12}/\text{cm}^2$
- Solution: Modulation doping from thin InAs(Si) quantum well.

Modulation Doping with Thin InAs(Si) Layer

30 Å InAs

100 Å AlSb

12 Å (4 ML) InAs(Si)

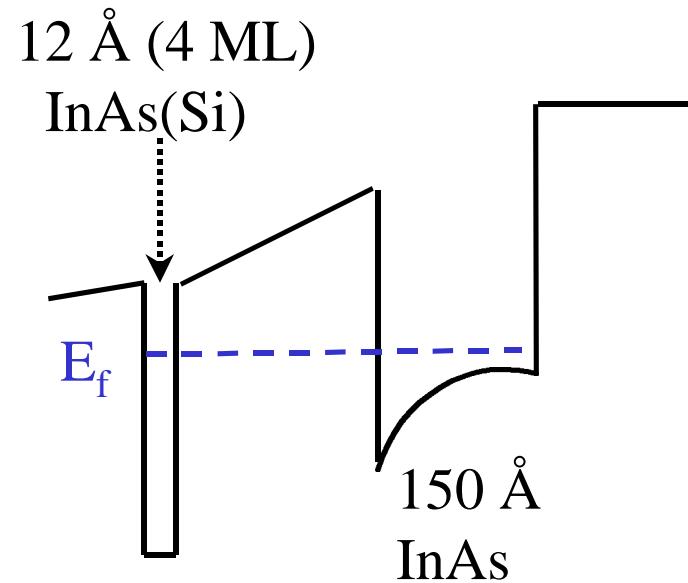
125 Å AlSb

150 Å InAs

2.0 μm AlSb

0.5 μm GaAs

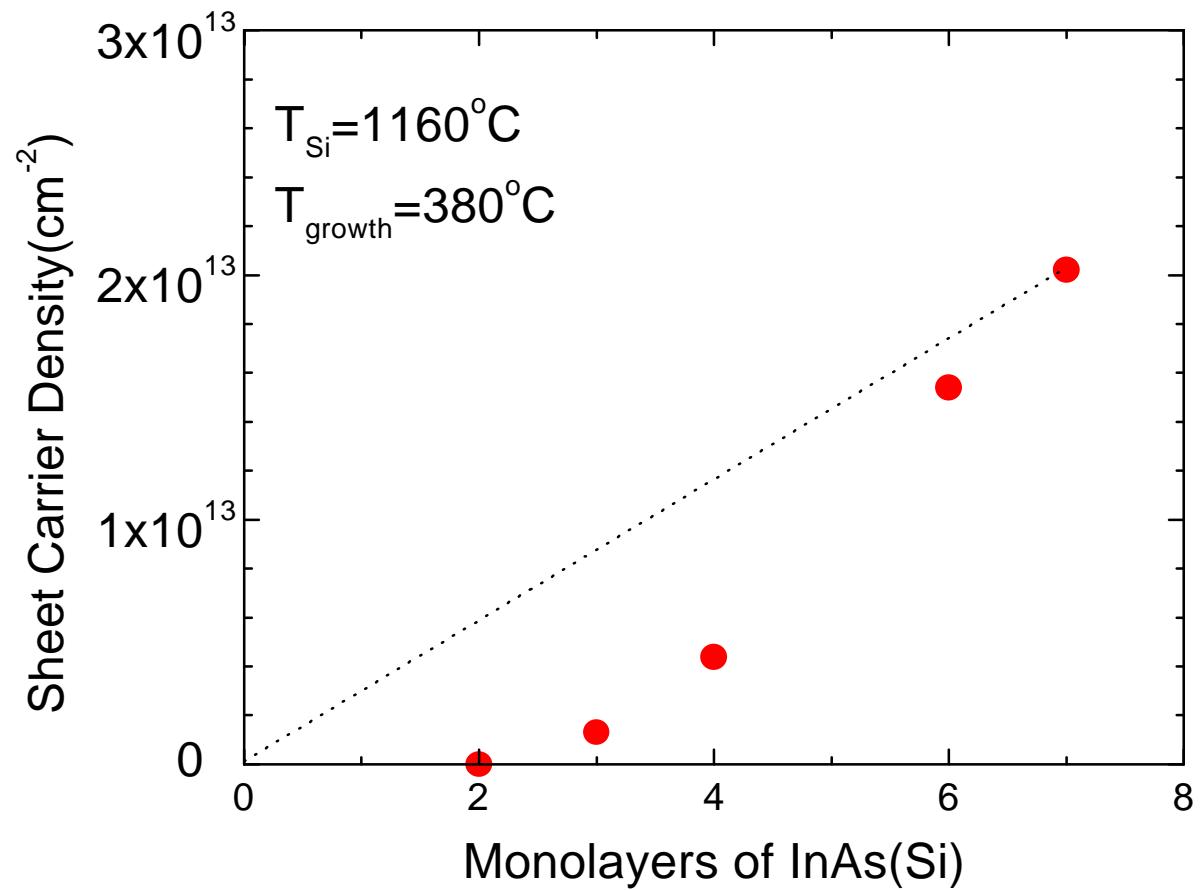
GaAs(SI) (001)



InAs(Si) Modulation Doping Experiments

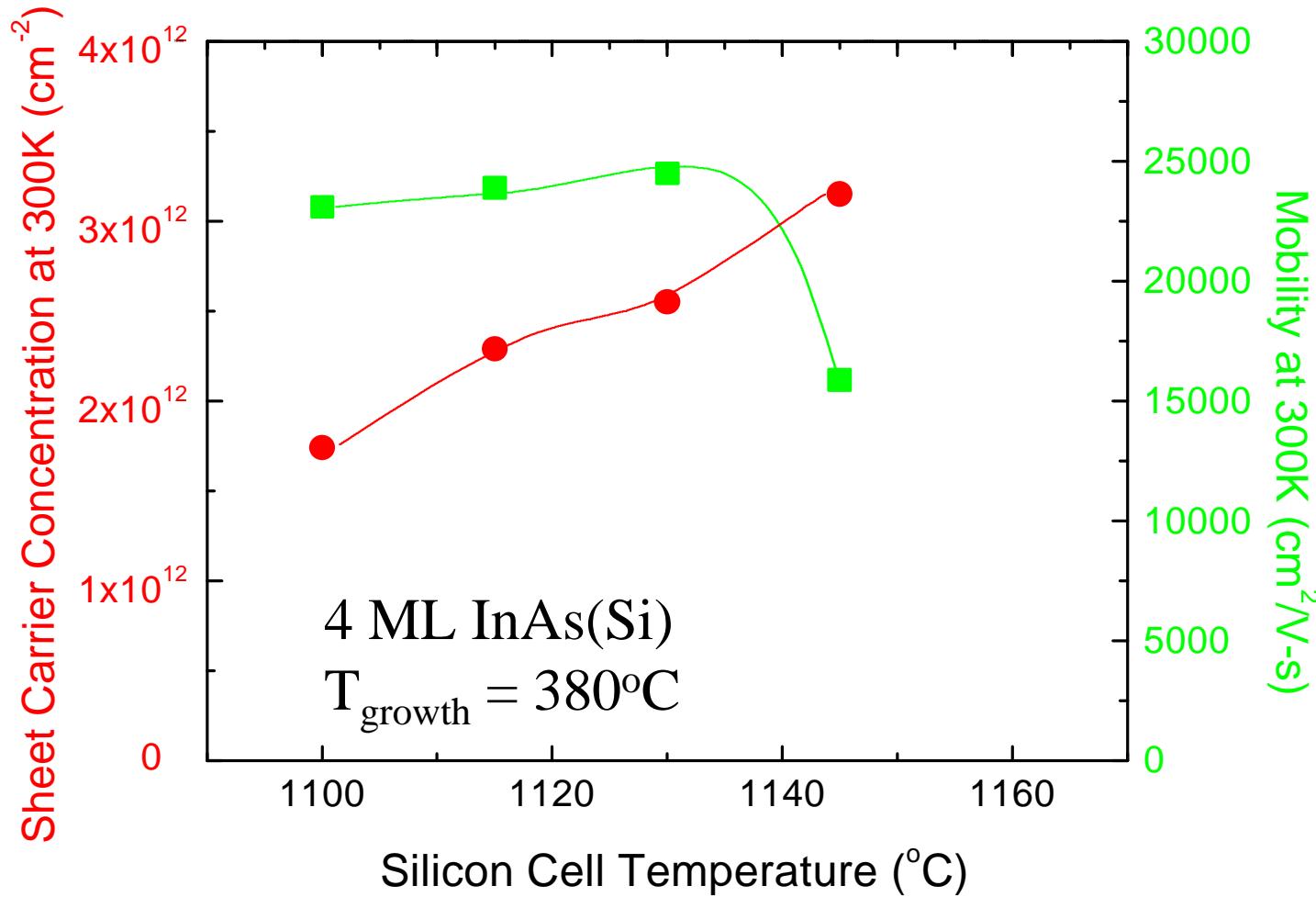
- Grew full structure: 4 ML InAs(Si) + 50 ML undoped InAs; growth temperature = 500°C
 - No effect on transport ($n_s < 10^{12}/\text{cm}^2$, $\mu \sim 25,000 \text{ cm}^2/\text{Vs}$)
- Grew thin InAs(Si) QWs clad by AlSb at 450-500°C
 - Highly resistive
- Grew thin InAs(Si) QWs clad by AlSb at 370-420°C
 - Conductive ($n_s > 10^{12}/\text{cm}^2$, $\mu \sim 100 \text{ cm}^2/\text{Vs}$)
- Grew full structure (4 ML InAs(Si) + 50 ML InAs) at 400°C
 - Success!!! ...high sheet density and high mobility

Transport results from thin InAs(Si)/AlSb single quantum wells



---> Choose InAs(Si) thickness of 4 ML

Modulation Doping with Thin InAs(Si) Layer



InAs(Si) layers on both sides
of well yielded $5.6 \times 10^{12}/\text{cm}^2$

Problem #2: excessive hole leakage currents

Problem #3: lack of a gate recess technology

Solution: Add an additional barrier layer that has a large valence band offset w/r to InAs and is chemically stable.

Choose $\text{In}_{0.4}\text{Al}_{0.6}\text{As}$, despite 5% lattice mismatch.

InAs/AlSb single quantum well for field-effect transistor applications

20 Å InAs

40 Å $\text{In}_{0.4}\text{Al}_{0.6}\text{As}$

12 Å AlSb

12 Å InAs(Si)

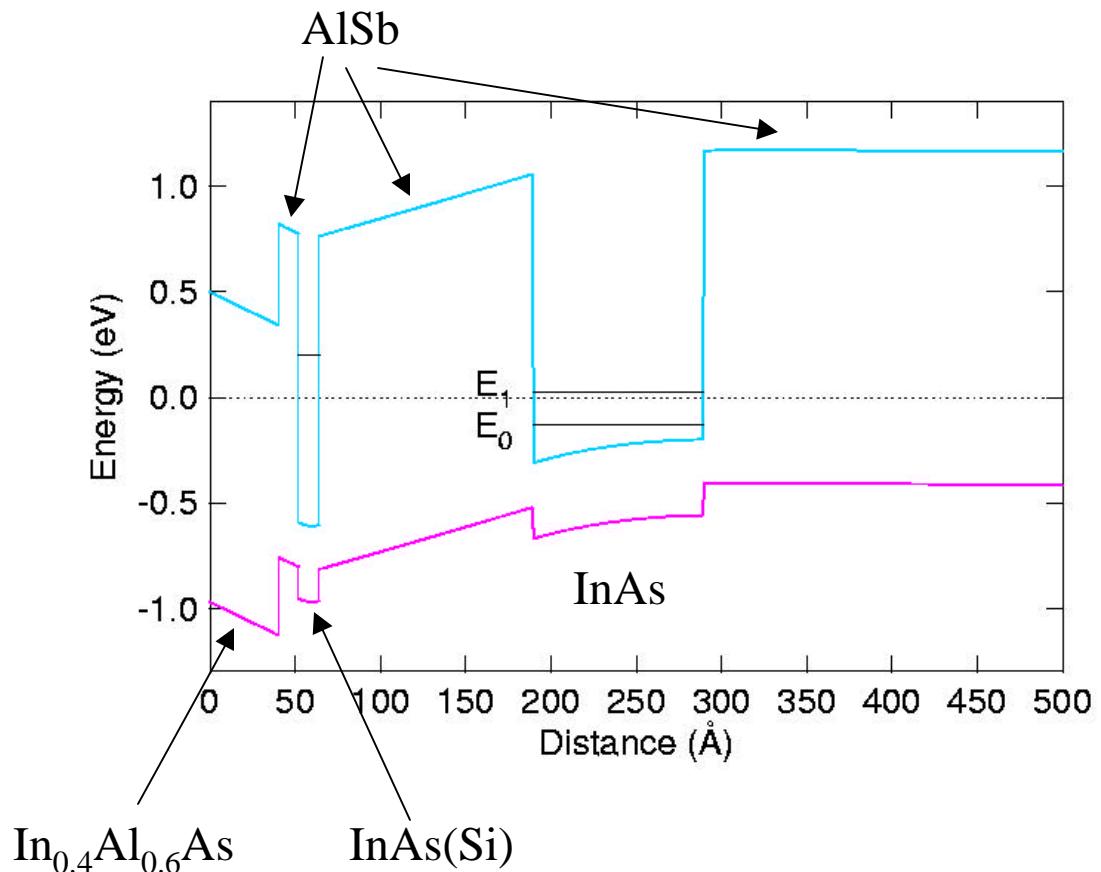
125 Å AlSb

100 Å InAs

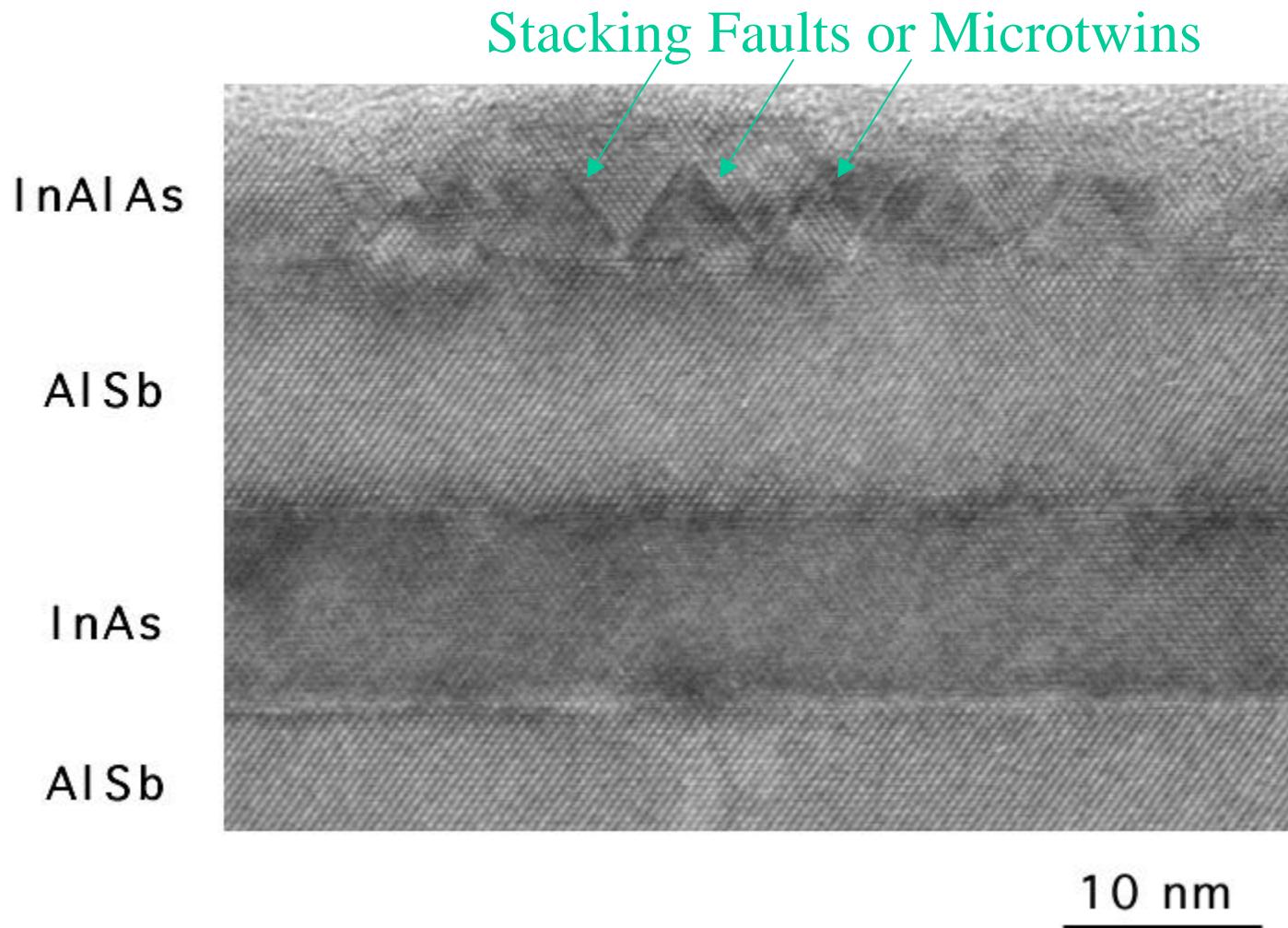
2.0 μm AlSb

0.5 μm GaAs

GaAs(SI) (001)

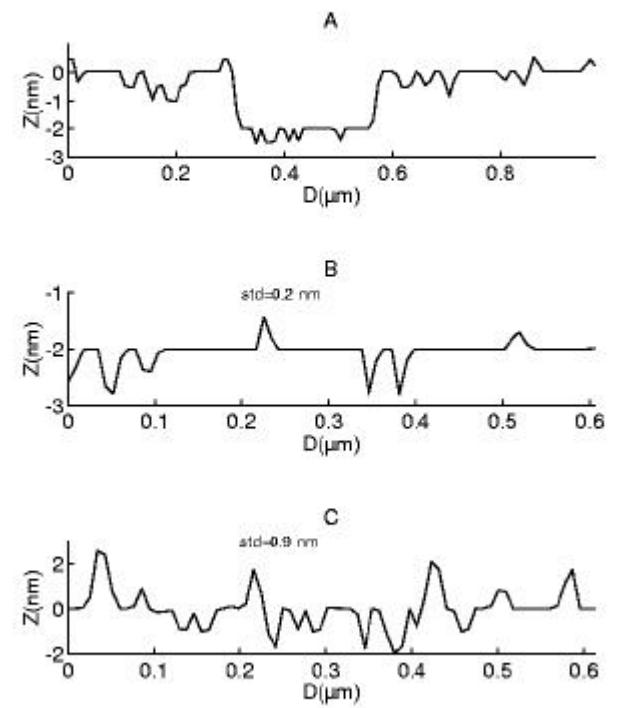
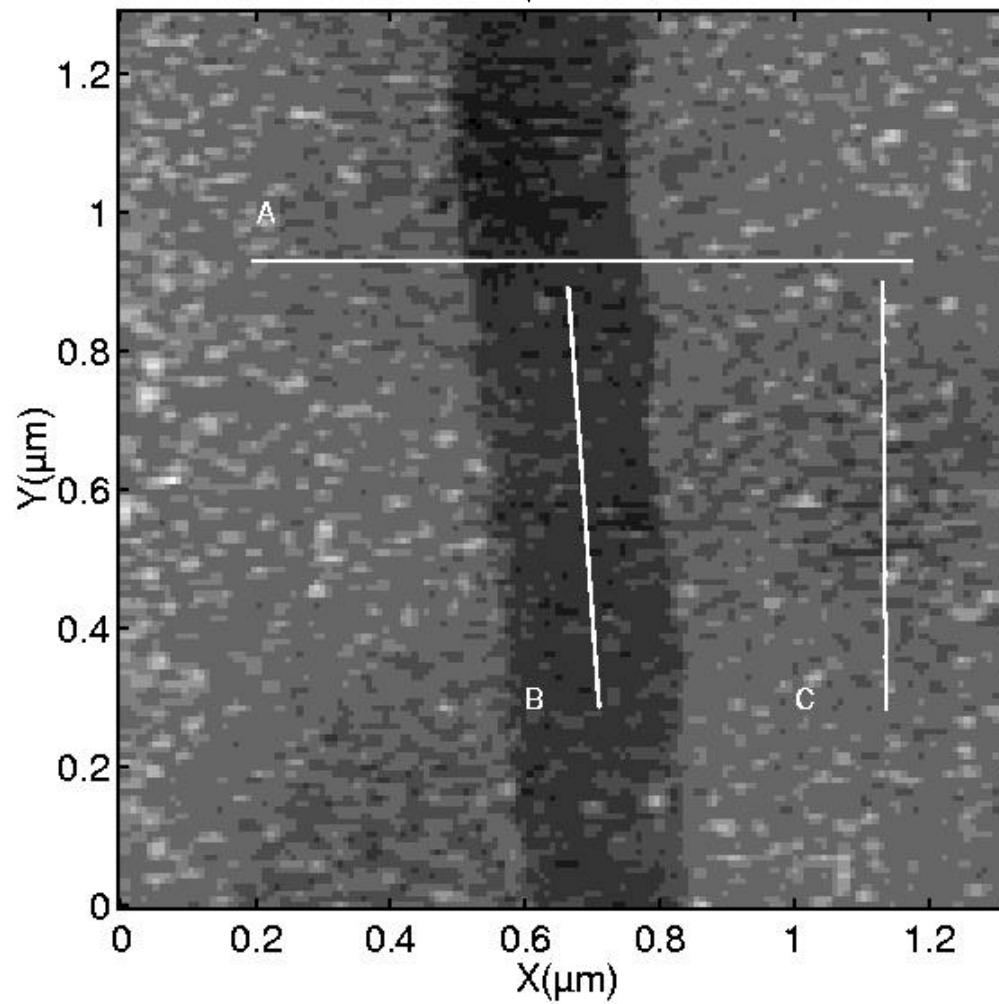


Transmission Electron Microscopy



AFM of InAlAs gate recess

2 nm InAs cap removed by acetic acid



Conclusions

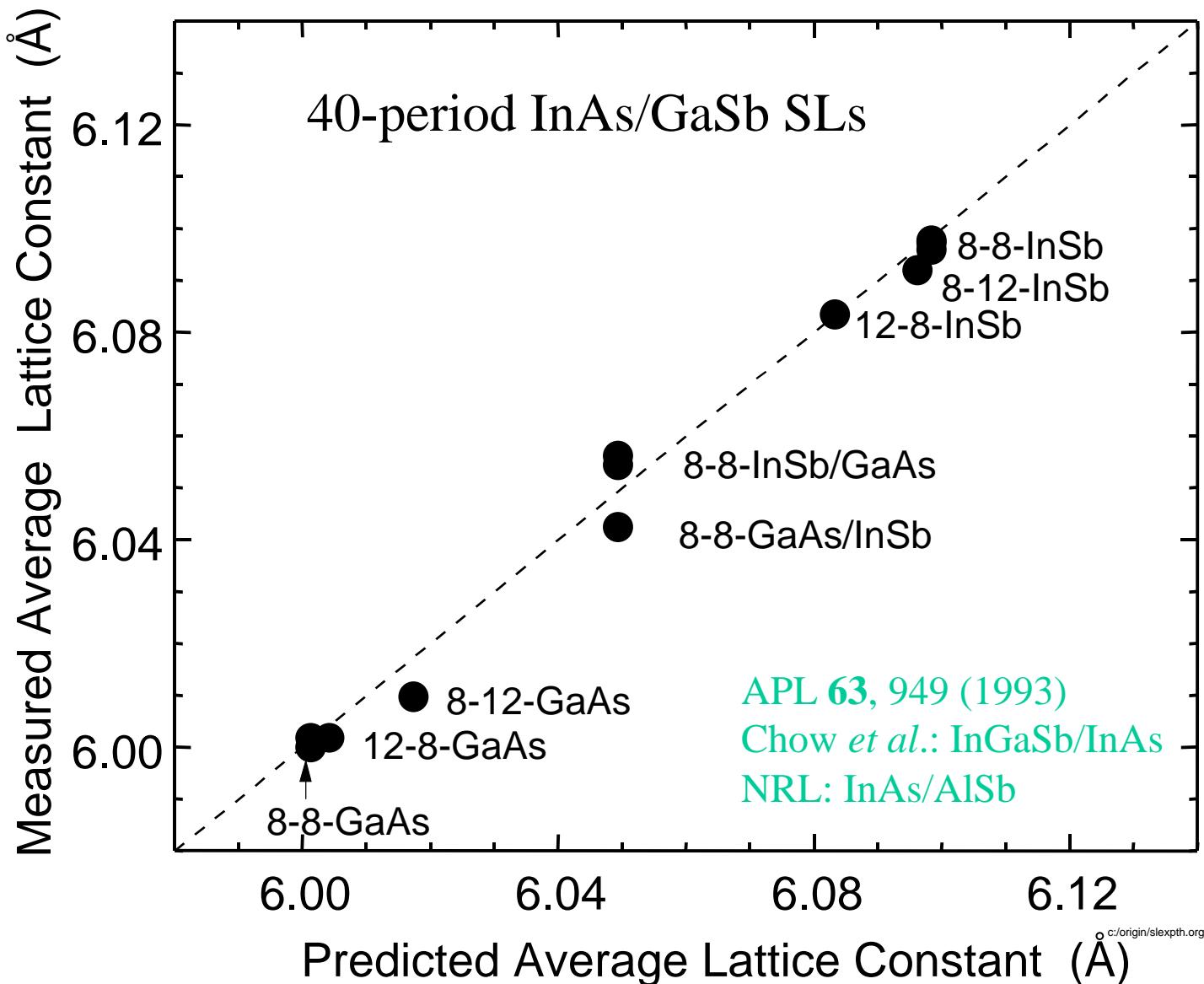
- Modulation InAs(Si) doping:
 - Low growth temperatures ($\sim 400^\circ\text{C}$) to minimize Si segregation into AlSb.
 - Achieved $3.2 \times 10^{12}/\text{cm}^2$ with $\mu=25,000 \text{ cm}^2/\text{Vs}$.
 - Y. Zhao *et al.*, *Trans. Elect. Dev.* **45**, 341 (1998)
 - B.R. Bennett *et al.*, *APL* **72**, 1193 (1998)
 - C.R. Bolognesi *et al.*, *EDL* **19**, 83 (1998)
- $\text{In}_{0.4}\text{Al}_{0.6}\text{As}$ barrier layers:
 - Chemically stable etch-stop allows gate recess.
 - Increased barrier for holes reduces leakage currents.
- HEMTs with excellent microwave properties:
 - $f_t = 100 \text{ GHz}$ at 100 mV

Monday Recap Session

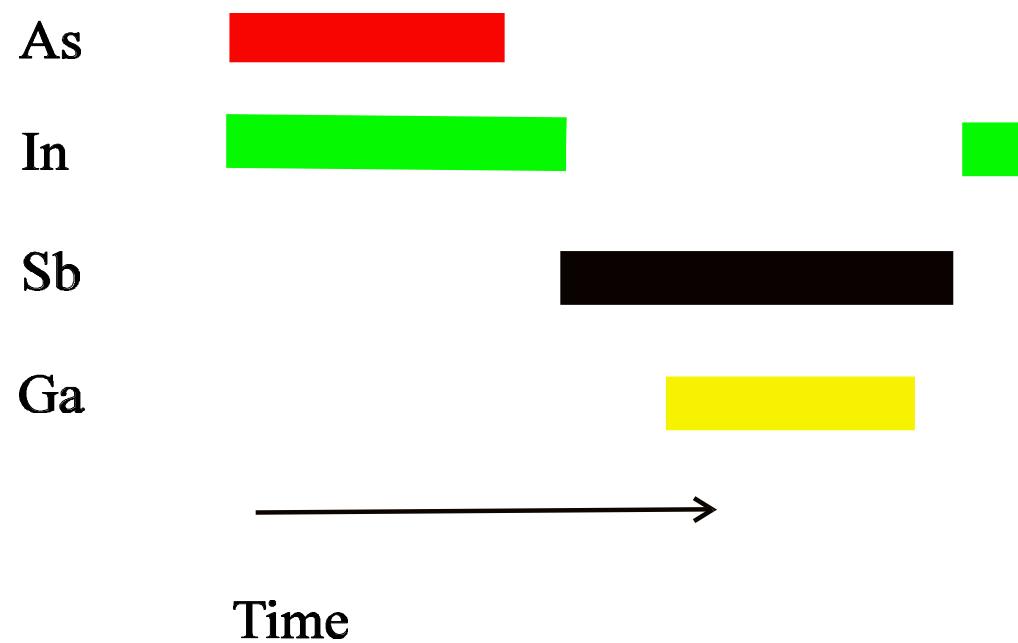
Alex Zunger Question #2

Do MBE growers have any idea what kind of interface bonds they are creating??

Control of Interface Bonds in InAs/GaSb SLs



Migration-Enhanced Epitaxy for InSb Interfaces



InAs/GaSb superlattices with varying interfacial bond type

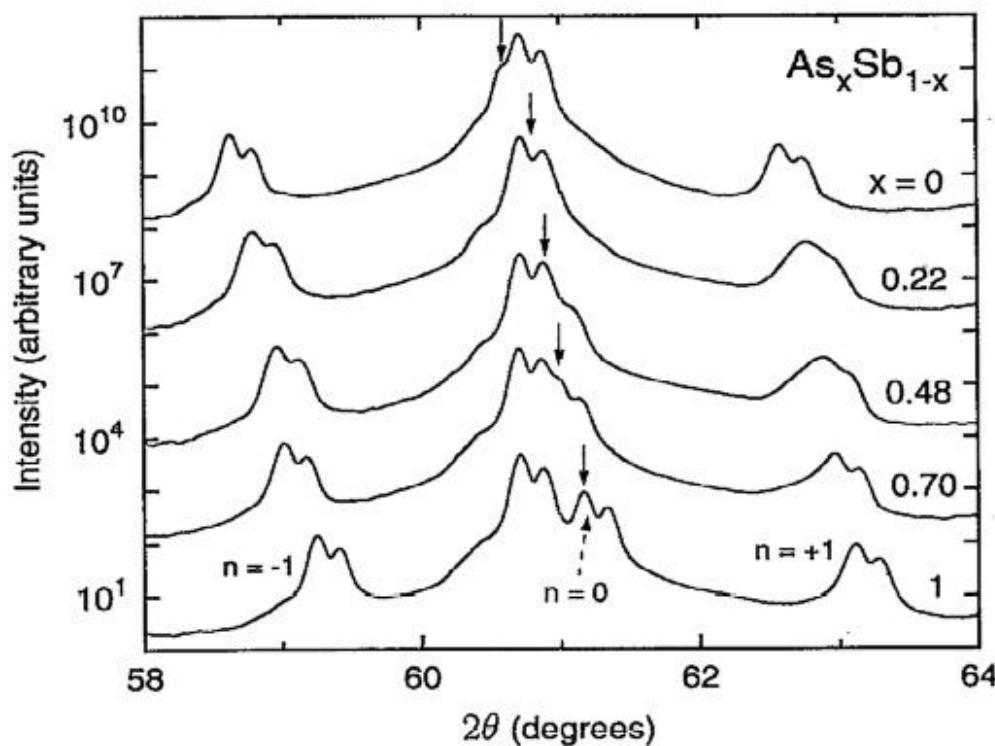
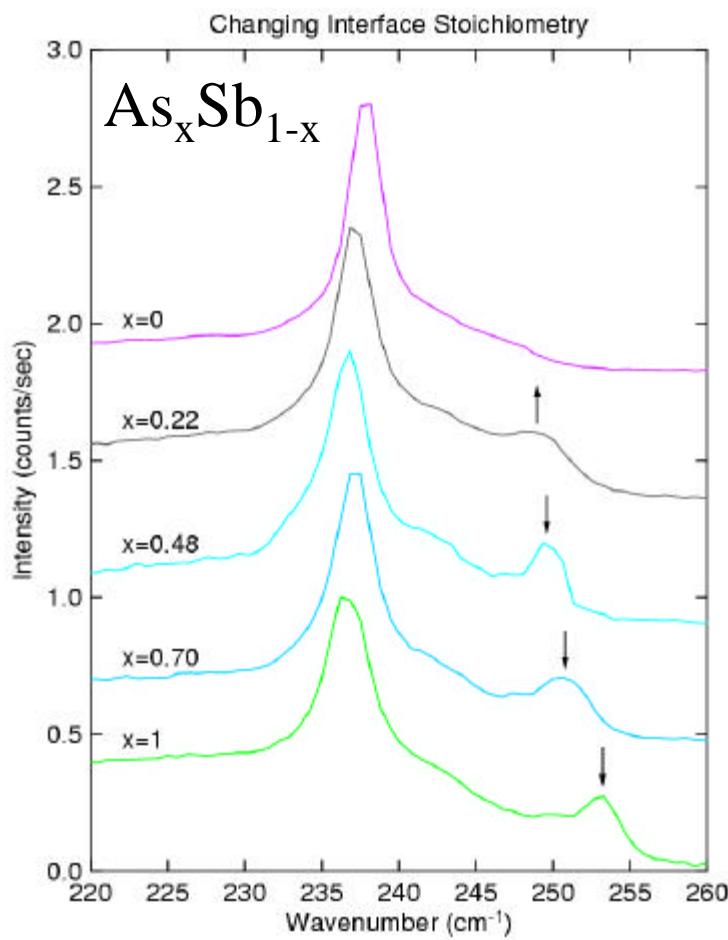


FIG. 1. X-ray-diffraction data from the InAs/GaSb superlattices as a function of the composition of the $\text{As}_x\text{Sb}_{1-x}$ plane that connects the InAs and GaSb layers. The arrows indicate the position of the $n = 0$ satellite. The large peaks at 60.7° and 60.9° arise from the $K\alpha_1$ and $K\alpha_2$ reflections off the GaSb buffer layer.

Raman Spectroscopy of InAs/GaSb SLs



- Intentionally grew SLs with mixed interfacial bonds
- Composition of interfaces from x-ray diffraction
- Position of vibrational mode is sensitive to composition
- Explained apparent discrepancies for energy of GaAs mode in the literature

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